BRIGHTNESS EVOLUTION FOR LHC BEAMS DURING THE 2012 RUN

M. Kuhn (University of Hamburg, Hamburg, Germany), G. Arduini, J.-F. Comblin, A. Guerrero, V. Kain, B. Mikulec, F. Roncarolo, M. Sapinski, M. Schaumann, R. Steerenberg, CERN, Geneva, Switzerland.

Abstract

One of the reasons for the remarkable achievements of the LHC is the excellent performance of the LHC injector chain. The evolution of the brightness in the injectors from 2011 to 2012 is discussed and the performance of the LHC in 2012 is shown. During certain run periods, the brightness from the beam provided by the injectors was lower than usual. Some of the issues have been identified so far and will be reported. The latest results on emittance blow-up investigations through the 2012 LHC cycle will also be presented and compared to the 2011 data. Possible implications for LHC upgrade scenarios will be mentioned.

INTRODUCTION

For achieving high luminosities in a particle collider it is crucial to produce high brightness beams in its injectors and preserve the brightness through the cycle of the collider. The LHC injector produces beams beyond design brightness. The record in 2011 was bunch intensity of 1.5×10^{11} protons per bunch with a transverse normalized emittance of 1.9 µm. These parameters could be even further improved during the 2012 run. The injectors routinely provide bunch intensities of 1.6×10^{11} and emittances of 1.5 µm. The excellent performance of the injectors is one of the main reasons for the outstanding luminosity reach of the 2012 LHC run in proton-proton physics. Despite the lower energy than design (4 TeV in 2012 instead of design energy of 7 TeV) peak luminosities of 7.7×10^{33} cm^{-2}s^{-1} could be reached, compared to the design luminosity of 10^{34} cm^{-2}s^{-1}. Table 1 summarizes the LHC 2012 run conditions.

Table 1: LHC Run Configuration 2012

Total number bunches for fill	1374
Max number bunches injected	144
Bunch spacing [ns]	50
Intensity/bunch	1.6×10^{11}
Crossing angle (ATLAS, CMS) [µrad]	290
Number of injections per fill and beam	12 (+1 pilot)
Filling time	~ 30 min
Number collisions (ATLAS+CMS/ALICE/LHCb)	1368/0/1262
Collision energy per beam	4 TeV
β* (ATLAS, CMS) [cm]	60

Nevertheless the initial brightness from the injectors is reduced in the course of the LHC cycle. This paper discusses the evolution of brightness in the LHC through 2012 and transmission and emittance preservation through the LHC cycle. Possible implications of the findings for the LHC high luminosity upgrade are given.

BRIGHTNESS EVOLUTION IN 2012

The evolution of beam brightness at the beginning of the LHC collisions and the end of the LHC injector chain, the extraction flattop of the SPS, is shown in Fig. 1. The larger spread on the SPS measurements is due to the few points in the wire scanner profiles and the hence less reliable fit result with the very small beams at SPS extraction energy of 450 GeV. The LHC results are taken from the peak luminosities of one of the high luminosity experiments, CMS. The results from the ATLAS experiment look similar.

Despite the large errors and the spread on the SPS measurements a clear reduction of brightness from SPS extraction to LHC collisions is apparent. On average the brightness is reduced by about 40 %.

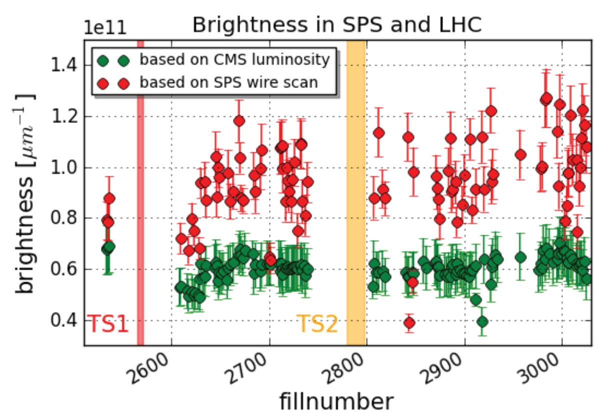

Figure 1: Brightness calculated from instantaneous luminosity in CMS during LHC collisions assuming 15 % error on β* and 5 % error on the crossing angle. The beam intensity measurement was taken from fast Beam Current Transformer (FBCT) in the LHC. For the emittance measurements in the SPS determined with wire scanners an error of 10 % is assumed. The two shaded areas in the plot, TS1 and TS2, indicate the LHC maintenance periods (Technical Stops).

Brightness from the Injectors

To constantly deliver the high performance and to meet the demands for higher and higher bunch intensities of the LHC, the LHC circular injector machines – the PSBooster, the PS and the SPS – have to continuously

ISBN 978-3-95450-118-2

work on the LHC beams. The injector machines are working partly close to their transverse or longitudinal stability limits. Occasionally the delivered brightness from the injectors is reduced with a clear effect on the LHC luminosities. An example is given in Fig. 2 and Fig. 3.

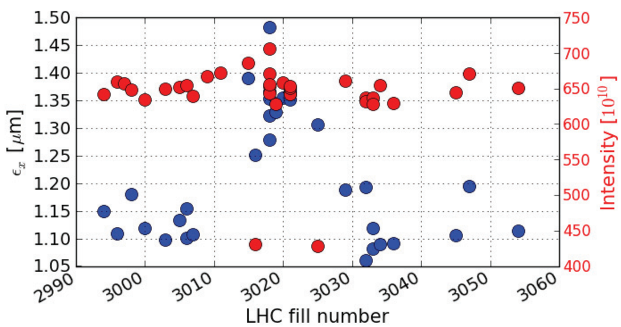

Figure 2: Horizontal normalized emittance and beam intensity at the PS flattop before extraction to the SPS. A change of the vertical working point at PS injection lead to larger horizontal emittances at flattop. Reverting the change re-established the smaller emittances. Period end of August, beginning of September 2012.

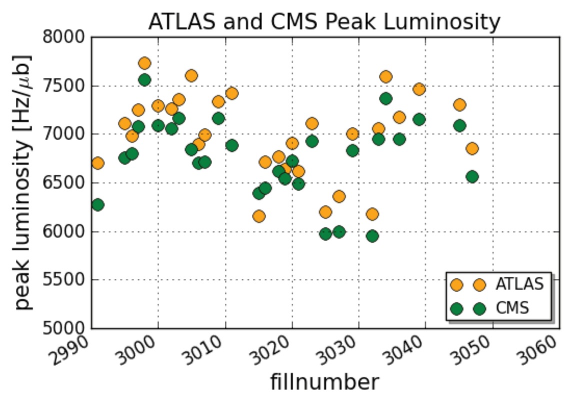

Figure 3: Peak luminosity in ATLAS and CMS. Period end of August, beginning of September 2012. The period of larger horizontal emittances from the PS, Fig.2, coincides with the smaller peak luminosities in the LHC. Other fills with lower peak luminosities afterwards are due to instabilities and subsequent beam loss in the LHC.

Another period with reduced brightness from the injectors occurred after Technical Stop 1, see Fig.1 and was caused among other effects by injection mismatch into the SPS due to the change of the fast extraction orbit in the PS. The extraction optics in the PS depends on the extraction trajectory due to the existence of stray fields in the extraction channel. The effect on the emittance at SPS injection is shown in Fig.4 and Fig.5. The mismatch results in larger emittances and a significantly larger non-Gaussian tail population. When the original extraction orbit in the PS had been restored the emittances were back to their original values.

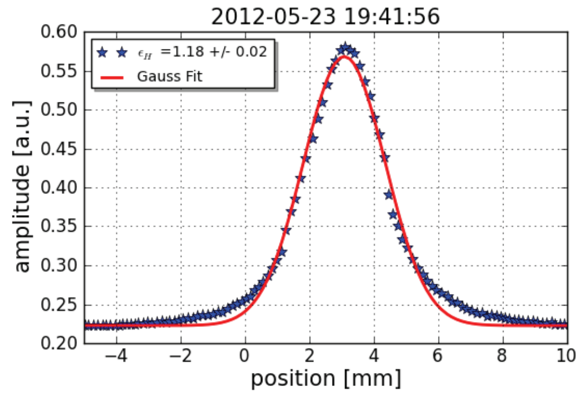

Figure 4: Reference beam profile at SPS injection (26 GeV) in the horizontal plane during a test of the sensitivity of the beam size to the PS extraction trajectory before any changes. Single nominal LHC bunch.

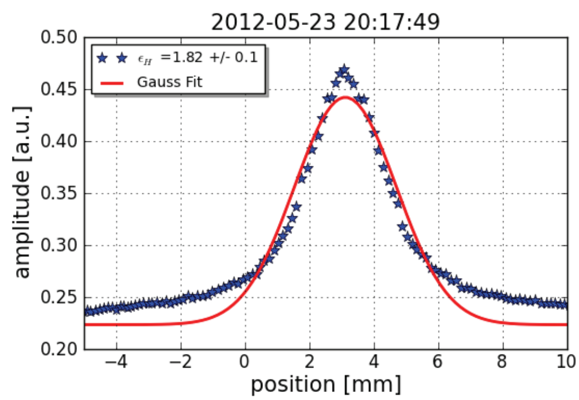

Figure 5: Horizontal profile at SPS injection on the same day as Fig.4 after changing the kick of the PS extraction kicker to alter the extraction trajectory. Single nominal LHC bunch. The change of the trajectory causes optics mismatch at injection into the SPS.

Continuous monitoring of the injector beam parameters is necessary to guarantee the required performance. Systematic measurements, logging of beam parameters and analysis of the measurement results is being put in place. Figure 2 is already one of the results of these efforts.

Brightness Reduction in the LHC

To fully exploit the large available aperture in the LHC and the small emittances from the injectors, the β* at the high luminosity experiments ATLAS and CMS was pushed down to 0.6 m for the 2012 run. As a consequence the primary collimators in the LHC had to be moved closer to guarantee enough margin in case of accidental beam loss. Hence towards the end of the 2012 ramp the primary collimators move to 4.3 σ (nominal sigma, 3.5 μm emittance) and stay there throughout high energy operation. These tight collimator settings have an impact on transmission. Depending on the tail population the losses reach up to 5 % under normal conditions through ramp and squeeze. Beam 2 always loses more than beam

ISBN 978-3-95450-118-2

1. Figure 6 shows the typical evolution of the beam intensities through ramp and squeeze in 2012. For comparison a plot of 2011 is shown in Fig.7. Despite the degraded transmission in 2012, the biggest reduction of brightness comes from emittance blow-up during the LHC cycle as was already the case in 2011, [1].

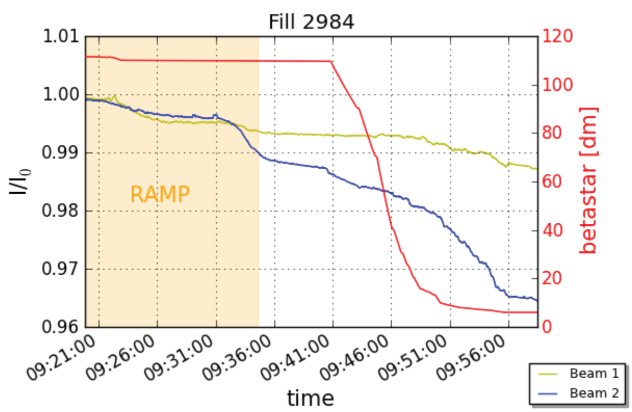

Figure 6: Relative intensity change for beam 1 and beam 2 during acceleration and β* squeeze in the LHC, measured with FBCT, fill 2984. Beam 2 is losing a factor 2 to 3 more.

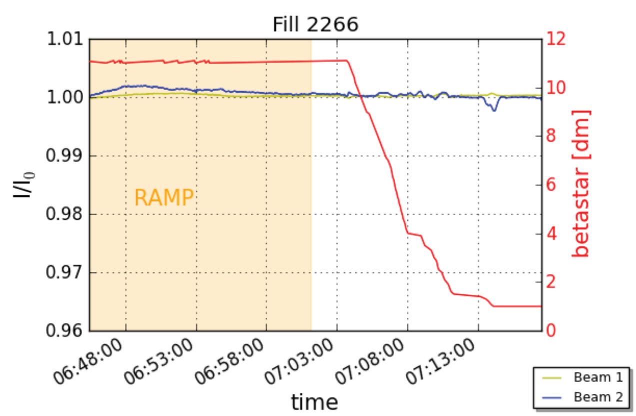

Figure 7: Relative intensity change for beam 1 and beam 2 during acceleration and β* squeeze in the LHC, measured with the FBCT. The loss of intensity is below the measurement accuracy of the device (< 0.1%). The FBCT measurement depends slightly on beam position and bunch length. The primary collimators were positioned at 5.7 σ in 2011.

2012 LHC EMITTANCE PRESERVATION

A summary of the emittance growth through the different phases in the LHC cycle is given in the following. A detailed analysis of the 2011 run can be found in [1].

The LHC Injection Plateau

As was already the case in 2011, the emittances in the vertical and horizontal plane are conserved within the measurement precision at injection from the SPS into the LHC (measurement precision ± 10 %). The LHC matching monitors are not operational yet. Wire scans at SPS flattop and right after LHC injection are used instead. Figure 8 shows an example of measurements in the SPS and in the LHC. The measurements in the LHC are bunch-by-bunch, whereas in the SPS an average for all bunches is given. The wire scanners in the SPS are at locations with small beta functions and the wire speed cannot be reduced due to issues with saturation. Only a few points are available per scan to obtain the Gaussian fit. Overlaying profiles of several scans however increases the accuracy significantly. This method was used to obtain the SPS numbers in Fig.8.

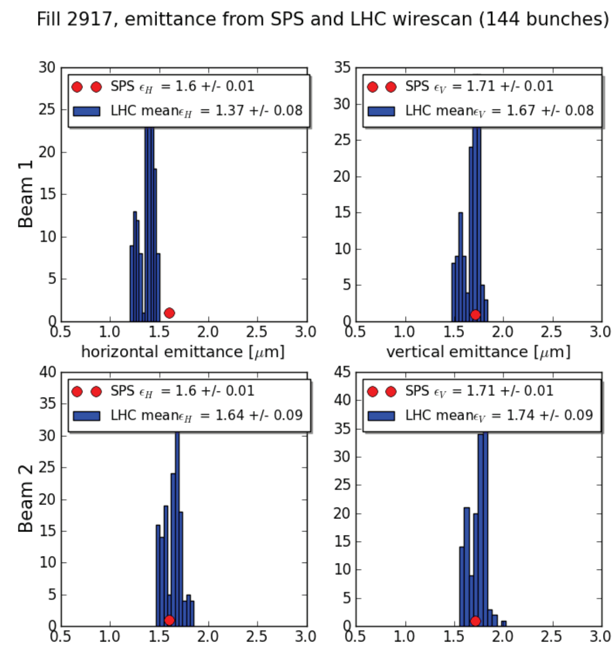

Figure 8: Wire scan histograms of normalized averaged emittance of 144 bunches at SPS extraction compared to bunch-by-bunch emittances at LHC injection.

While the beams are waiting on the LHC injection plateau until the filling is finished, the horizontal emittances grow. The typical growth rate is about 10 % in 20 minutes for the LHC beam parameters. This blow-up is consistent with intra beam scattering (IBS) simulations [2]. As the different batches are injected at different moments during the 30 minute filling time and therefore do not all suffer from the same blow-up, IBS blow-up is still the smallest contribution to the total observed growth. Longitudinal batch-by-batch blow-up has been tested. The different batches can be blown up to a target bunch length value within the first minutes after injection without affecting the already circulating batches [2]. The decreased 6 dimensional phase space density should help to reduce the IBS growth in the transverse plane. Emittance measurements during the tests did not show a clear gain. More tests will follow.

ISBN 978-3-95450-118-2

Other sources of blow-up during the injection plateau will also be investigated (e.g. noise and the effect of the damper).

The LHC Ramp

The results of the 2011 studies show similar relative emittance growth of about 20 % for both beams and both planes for initial emittances of about 1.6 µm. The 2012 measurements indicate that measureable growth only occurs in the horizontal plane and more for beam 2 than for beam 1. The growth in the horizontal plane of beam 2 is 15 - 20 % for initial emittances of about 1.6 µm and < 10 % for beam 1. Note that beam 2 is also losing more intensity during ramp and squeeze than beam 1, see Fig. 6, which could be due to the larger blow-up.

The only available instruments to measure transverse emittances through the ramp are wire scanners. The LHC Beam-Gas Ionization monitor (BGI) is only operational for beam 2 and the calibration is still not fully understood. Wire scanners can only be used with low intensity. At several occasions scans were done through the ramp with a few bunches per ring. An example for beam 2 horizontal is shown in Fig.9. Two batches of 6 bunches were accelerated and wire scans were frequently taken. The growth in the horizontal plane during the injection plateau and during the ramp is clearly visible. The emittances increased by ~ 15 % for an initial emittance of 1.6 – 1.7 µm. The results are summarized in Table 2. Note also that the emittances seem to decrease slightly towards the end of the squeeze, showing uncertainties on the assumed optics at the wire scanner locations.

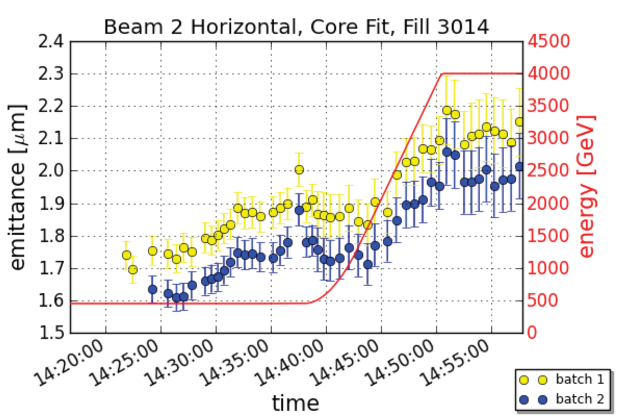

Figure 9: Wire scans of beam 2 horizontal during injection and ramp of fill 3014 with 2 batches of 6 bunches each. The cores of the transverse profiles were fitted with a Gaussian Function. Error bars indicate error in measured beta functions, fitting error and average of in and out scan.

It is also not clear how representative the low intensity test fills, where measurements can be taken, are for high intensity physics fills. Using the emittance obtained from the LHC luminosity rather indicates a growth of about 40 % from typically 1.7 µm from the SPS to 2.4 µm in collision, which is more than we see during the test fills. The BGI cannot measure during the test fills but during the high intensity physics fills. It also shows significant emittance growth during the ramp for beam 2 horizontal, see Fig. 10. The absolute numbers can however not be trusted yet. For future emittance studies the BGI should give reasonable results. A comparison with the wire scanner results will then be possible.

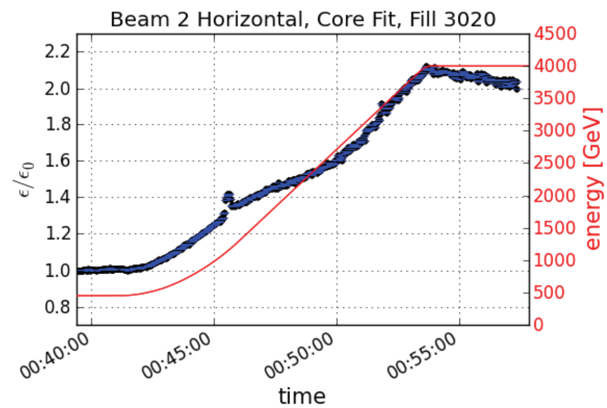

Figure 10: BGI measurement of beam 2 horizontal during ramp of physics fill 3020 with 1374 bunches. The cores of the transverse profiles are fitted with a Gaussian.

Table 2: Normalized Emittances of Beam 2 Horizontal for Fill 3014.

ε [µm]	**Batch 1**	**Batch 2**
Injection	1.696 ± 0.043	1.609 ± 0.041
Before ramp	1.890 ± 0.049	1.781 ± 0.047
Flattop	2.187 ± 0.105	2.060 ± 0.103
Squeeze	2.111 ± 0.102	1.969 ± 0.099
Collision	2.039 ± 0.060	1.885 ± 0.058

The LHC Squeeze

Unlike to 2011 no significant growth seems to occur during the squeeze. Fast scans with the LHC synchrotron light monitor during physics fills do not show any blow-up of the beam sizes within the uncertainties of the measurement. This is also consistent with the wire scanner results in Table 2.

IMPLICATIONS FOR OPERATION AFTER LONG SHUTDOWN 1 AND LHC UPGRADE

The proposed parameters for the high brightness 25 ns batch compression beam [3] and the maximum parameters for the LHC Injector Upgrade for the LHC High Luminosity era [4] give a similar brightness as the 2012 50 ns beams. The IBS growth rates will therefore also be similar to what is observed now in the LHC. Currently there is about 10 % difference in specific luminosity between the first injected batches and the last injected batches. Longitudinal batch-by-batch blow-up

ISBN 978-3-95450-118-2

applied right after the injection of each batch should reduce the effect. Batch-by-batch blow-up will be put into operation towards the end of the 2012 proton run. Otherwise effort should be spent on reducing the filling time. The design filling time is about 15 minutes, compared to the 30 minutes currently needed to fill the LHC.

The 2011 results indicate that the total absolute growth from SPS flattop to LHC collisions is independent of bunch intensity and initial emittance [1] (~0.5 μm growth). The results of 2012 from physics fills and one fill with the PS batch-compressed beam [3] also point in this direction (~0.7 μm growth for the convoluted emittance in the SPS to the emittance from luminosity in the LHC). This effect if not cured could spoil the performance of the proposed 1μm beams obtained by PS batch compression. The largest contribution of the growth occurs during the ramp in the horizontal plane. The origin of this growth is still not clear, noise is a possible candidate. The impact of more damper gain during the ramp will still be investigated during the 2012 run.

CONCLUSION

The performance of the LHC is tightly linked to the performance of the injectors. The evolution of the peak luminosity of the LHC follows the evolution of the brightness in the injectors. The high brightness 50 ns beam produced in the injectors however significantly loses brightness in the course of the LHC cycle. The transmission through the cycle is worse than in previous LHC years due to tight collimator settings necessary for the low β^* at the high luminosity experiments. The main reduction of brightness comes however from the significant emittance blow-up through the cycle. The growth mainly occurs in the horizontal plane during the injection plateau, consistent with IBS, and during the ramp. 2012 data shows that beam 2 might be affected more by blow-up during the ramp than beam 1. The total blow-up from SPS flattop to LHC collisions, using the emittance values obtained from the LHC luminosities is about 40 % for initial emittances of 1.7 μm. The origin of the emittance growth during the ramp is not clear. The effect of the gain of the transverse damper will be investigated. Longitudinal batch-by-batch blow-up is being put in place in the LHC to counteract the effect of IBS in the transverse plane at the injection plateau.

REFERENCES

[1] V. Kain et al., "Emittance Preservation in the LHC", LHC Performance Workshop, Chamonix, France 2012.

[2] M. Kuhn et al., "Causes and Solutions for Emittance Blow-Up during the LHC Cycle", IPAC 2012, New Orleans, Louisiana, USA.

[3] H. Damerau et al., "Performance Potential of the Injectors after LS1", LHC Performance Workshop, Chamonix, France 20012.

[4] O. Bruning et al., "HL-LHC Operation with Protons and Ions", LHC Performance Workshop, Chamonix, France 2012.

ISBN 978-3-95450-118-2